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Search for Heavy Leptons and Hard Penetrating Radiation in the Neutrino Beam, Study of Diffraction Scattering of Neutrinos; Study of Deep Inelastic ν_μ Scattering in a Ne Bubble Chamber at NAL, and Test of the $\Delta S = \Delta Q$ Rule at High Momentum Transfer Using Inclusive Reactions

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ABSTRACT

We prospose here an experiment designed to search for the existence of heavy leptons (λ^+) produced in the collisions of 400 GeV/c protons with matter in the beam dump. These charged leptons, which are assumed to decay by weak interaction will be detected by the interactions of their neutrinos ($\nu_\lambda, \bar{\nu}_\lambda$) in a Ne bubble chamber. For leptons with masses of greater than 1 GeV, the λ life time is expected to be too short for the lepton to be observed visually, therefore, the lepton must be identified by a detailed comparison with ordinary ν_μ interactions. We request 200,000 pictures with the beam protons hitting the shield directly and 200,000 pictures with the normal high energy ν_μ beam. <u>In the latter pictures</u> we will study deep inelastic ν_μ scattering, search for muonless ν_μ interactions, search for ν_μ diffractive processes and search for $\Delta S = -\Delta Q$ in strange particle production processes. This experiment <u>does not</u> require the EMI or a plate in the bubble chamber although the latter would be very useful and can run without the horn.

June, 1970

Contents

1. Introduction

The existence of still heavier charged leptons than the muon is clearly of great interest. The discovery of these leptons would perhaps shed some light on the existence of the muon and the nature of the interaction responsible for the (μ-e) mass difference. We can anticipate two interesting aspects of such heavy leptons:

1. They will carry their own lepton number, therefore, suggesting the existence of a new neutrino.
2. It is likely that their lifetime will be sufficiently short so that direct discovery, say by a mass search, will be impossible even at NAL.

Therefore, in all probability, these heavy leptons will not easily reveal themselves to us. In this proposal we suggest a technique of searching for heavy leptons ($\lambda\bar{\lambda}$) that are produced in the shield by either the incident protons or the large flux of electrons or photons obtained through π^0 production. This idea follows the experiment to be run at SLAC by Mann and Schwartz.[1] However, we believe that our sensitivity will be much greater. It is pointed out that the identification of ν_λ interactions and separation from the more copious ν_μ interactions is made possible through the combination of a visual technique and the unique features of a heavy liquid detector. The details of the proposed technique for a heavy lepton search at NAL will be discussed in sections 2 and 3.

There will be many fallout experiments from the Ne bubble chamber exposure proposed here. These experiments, which are of considerable interest in their own right and are unique to the Ne chamber, fall into several distinct categories which are discussed in sections 4, 5, 6 and 7. In section 9 we discuss in detail the time scale and the magnitude of the exposure requested and in section 8 we discuss the philosophy of our experiment technique and compare it to the other approaches suggested for neutrino experiments at NAL.

2. Production of Heavy Lepton Pairs by Protons and Sensitivity of the Heavy Lepton Search

(a) Heavy lepton pair production rates

1. Hadroproduction of $\lambda\bar{\lambda}$ pairs. We assume a $\lambda\bar{\lambda}$ production cross section of $\sim 10^{-33}$ cm^2/nucleon (this is the order of magnitude of the cross section observed by Christenson and Lederman in their AGS experiment). The number of $\lambda\bar{\lambda}$ pairs produced per pulse would be $\sim 2 \times 10^6$. The leptons should be strongly collimated forward.

2. Photoproduction of $\lambda\bar{\lambda}$ pairs. We expect that $\sim 10^{14}$ photons will be produced each pulse coming from π° decays. The rate of photoproduction of $\lambda\bar{\lambda}$ pairs goes like the inverse of the mass squared. The relative rate for $\lambda\bar{\lambda}$ production to e^+e^- production is given as

$$\left(\frac{m_e}{m_\lambda}\right)^2 \sim 10^7$$

for $m_\lambda = 3$ GeV. Using the fact that almost all the photons make e^+e^- pairs we find a $\lambda\bar{\lambda}$ production rate of

$$\sim 10^{14}/10^7 \simeq 10^7 \lambda\text{'s/pulse.}$$

Electroproduction (from the electrons produced by pair production) and the decay of high mass vector mesons might also contribute a comparable rate.

Thus, it is not unreasonable to expect that the order of $\sim 10^6 - 10^7$ $\lambda\bar{\lambda}$ pairs will be produced each machine pulse. We assume that because of the strong collimation of the $\lambda\bar{\lambda}$, 10% of the $(\nu_\lambda,\bar{\nu}_\lambda)$'s from the λ decays will pass through the bubble chamber.

(b) Rate of Production of $(\lambda, \bar{\lambda})$'s in the Ne Bubble Chamber

Assuming a 15 ton fiducial volume of Ne we find that 5×10^5 pictures would give 10 events if there were 2.5×10^6 ν_λ's incident on the chamber per pulse. This assumes that the ν_λ interaction cross section is the same as that of ν_μ's of 10 GeV. This is the same order of magnitude of ν_λ flux that might be crudely guessed to come from interactions in the shield.

The order of magnitude guesses listed above for the $(\lambda, \bar{\lambda})$ production and for the ν_λ detections indicate that it is not unreasonable to expect that the production of heavy leptons in the shield could be detected in the bubble chamber.

3. Experimental Technique for the Detection of ν_λ

Heavy lepton production by $(\nu_\lambda, \bar{\nu}_\lambda)$ would occur through the processes

$$\nu_\lambda + n \rightarrow \lambda^- + \text{(anything)} \tag{1}$$

$$\bar{\nu}_\lambda + p \rightarrow \lambda^+ + \text{(anything)} \tag{2}$$

with the leptons decaying by

$$\lambda^\pm \rightarrow \pi^\pm \nu_\lambda \tag{3}$$

$$\lambda^\pm \rightarrow \mu^\pm \nu_\mu \nu_\lambda \tag{4}$$

It has been estimated that for $M_\lambda > 1$ GeV the decay processes (3) and (4) will be equally probable.[2] In addition it has been estimated that the lifetime of the $\lambda^\pm$ will be less than $\sim 10^{-11}$ seconds for $M_\lambda > 1$ GeV. Therefore, it would seem unlikely to directly observe the trajectory of the $\lambda^\pm$ even in a bubble chamber.

The most likely method of discovery for the $\lambda^\pm$ would be to infer the existence of these particles through the characteristics of the decay modes (3) and (4). In the case of decay modes (3) the event signature will be the observation of single or multiple $\pi^\pm$'s being produced with high transverse momentum relative to the neutrino beam direction. Provided such events can be separated from hadron interactions this will be a clean signature since ν_μ interactions will not usually produce a pion unaccompanied by a μ (see, however, section 4). Since ν_λ and $\bar{\nu}_\lambda$ are produced with equal rate in the shield equal numbers of fast π^+ and π^- events should be observed. Since the Ne bubble chamber is ≥ 6 collision lengths across, hadron produced events should be clustered near the entrance of the bubble chamber whereas ν_λ produced events will be uniformly spread out. For neutrons interactions that are in equilibrium with the ν_μ coming through the shield the interaction rate will scale with the ν_μ flux whereas the rate for λ production will be $\sim$ independent of the ν_μ flux.

The decay mode (4) may not provide a relatively unique signature in that these events would also look like ordinary ν_μ interactions with high transverse μ momentum. However, a detailed comparison of the μ transverse momentum distribution for a sample of events that were enriched with $\lambda^\pm$ production may yield evidence for λ production. The isolation of both decays (3) and (4) would provide very strong evidence for the existence of $\lambda^\pm$ leptons. Process (3) can perhaps be used to estimate the mass of the $\lambda^\pm$.

There will be two steps, therefore, in the experimental heavy lepton ($\lambda^\pm$) search, each requiring $\sim$ 500,000 pictures of the Ne bubble chamber;

A. The primary protons are transported all the way to the shield. Heavy leptons as well as the common strongly interacting particles will be produced. The heavy leptons as well as any other short lived particles all decay. However, the strongly interacting particles are absorbed within $\sim$ 1.5 collision length. The production of the new leptons is revealed through the ν_λ interaction in the Ne bubble chamber. The high energy ν_μ neutrinos coming from π and K decay are suppressed relative to those produced at the ν target by a factor of

$$\sim \frac{(1.5 \text{ collision length in Fe})}{600 \text{ M}} \simeq 1/3000$$

Thus, the background in the bubble chamber coming from ordinary ν_μ interactions is strongly suppressed. All events produced in the bubble chamber will be carefully studied for evidence of these anamolous neutrino interactions.

B. The primary proton beam is made to hit the ν target and ordinary ν_μ interactions in Ne are carefully studied. In particular the transverse momentum distribution of the select event configurations which are also signatures for heavy lepton production is studied as well as the production of events with single or multiple pion production.

The first test for anamolous events will be to check to see if the rate of these events scales like the neutrino flux. If the rate scales like the flux then the event is most likely due to ν_μ interactions or hadronic interactions coming from the hadrons produced in the back of the shield by ν_μ's.

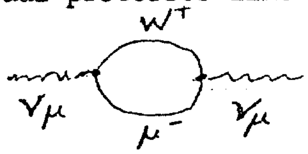
Event configurations that do not scale as the flux and which appear anamolous compared to ordinary ν_μ interactions will be studied in detail.

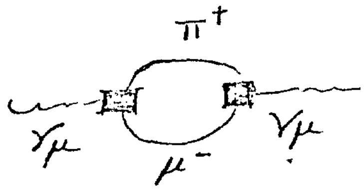
Finally, if there were some <u>new</u> penetrating radiation produced in the beam dump, it could likely be detected in this experiment. We emphasize that a 15' bubble chamber filled with Neon is perhaps the most powerful analytic device for discovering new phenomena. This is because of the visibility, charge measurement, photon conversion, electron identification and the number of interaction lengths contained in the bubble chamber. A number of processes have been 'first' observed in chambers with such properties such as Ke_4 decay, $K \to \pi\pi\gamma$, $K^+ \to \pi^\circ\pi^\circ e^+\nu$, $K^\circ_S \to \pi e\nu$, as well as the ν interactions in the CERN bubble chambers. We feel that similar observations can be made at NAL with the 15' chamber filled with Neon.

4. Attempt to Measure the Charge Radius of the Muon Neutrino - Detection of Muonless Neutrino Interactions

(a) Theory

The ν_μ is expected to have a charge radius due to virtual processes like





Diagrams of this type are expected to give a charge radius of the size $\langle r^2\rangle_\omega \sim g^2\ (h/M_W c)^2 \sim Gm_n^2\ (h/M_n c)^2 \simeq 10^{-32}(\mathrm{cm.}^2)$[3,4,5,6]. Protons can couple to the intermediate state charged particles subsequently resulting in electromagnetic scattering processes;

$$\nu_\mu + p \to \nu_\mu + p \quad . \tag{1}$$

$$\nu_\mu + p \to \nu_\mu + \text{(anything)} \tag{2}$$

Several estimates have been made for the rate of process (1) in terms of the W mass and of the cross section for

$$\nu_\mu + n \to \mu^- + p \tag{3}$$

Bernstein and Lee have estimated that process (1) will be down by $\sim 10^{-4}$ from process (3).[3] They find

$$d\sigma_{\nu\nu} = \left[\frac{1}{4} - \frac{1}{137}\,\frac{(q^2 + M_W^2)}{M_W^2}\ f(q^2)\right]^2 d\sigma_{\nu\mu} \tag{4}$$

where $f(q^2)$ is expected to be a slowly varying function of q^2. The term in brackets is proportional to the charge radius of the ν_μ neutrino. (For example, single π production scattering can be written as

$$\frac{d\sigma(\nu p \to \nu p\pi)}{d\sigma(ep \to ep\pi)} = q^4/30\ \langle r^2\rangle^2$$

where $\sqrt{<r^2>}$ is the ν_μ charge radius). For large W mass and large q^2 this gives $(f(q^2) \sim 4)$.[3]

$$d\sigma_{\nu\nu} \simeq 10^{-5}\, d\sigma_{\nu\mu}$$

Thus, for $\sim 10^5$ quasi elastic events there will be ~ 1 elastic ν_μ scatter. The collection of 10^5 quasi elastic events at high momentum transfer is a formidable task. However, present speculations lead to the expectation that the deep inelastic scattering cross section will be appreciable. Thus, if (4) continues to hold for these deep inelastic scatters (reaction 2) we expect

$$d\sigma_{\nu\mu \to \nu(\text{anything})} \simeq 10^{-5}\, d\sigma_{\nu N \to \mu + \text{anything}}$$

or alternately in terms of the charge radius

$$d\sigma_{\nu N \to \nu(\text{anything})} = \frac{q^4 <r^2>^2}{32}\, d\sigma_{eN \to e + (\text{anything})},$$

for $q^2 = 10(\text{BeV/c})^2$ and assuming $<r^2> \sim 10^{-32}\text{cm}^2$, this gives

$$d\sigma_{\nu N \to \nu + \text{anything}} \simeq 4 \times 10^{-39}\text{cm}.$$

Taking $e + N \to e + (\text{anything})$ cross sections as pessimistic a nanobarn (10^{-33} cm^2) we obtain

$$d\sigma_{\nu N \to \nu + (\text{anything})} \simeq 4 \times 10^{-39}\text{cm}.$$

With the apparatus described in this proposal we expect to be able to detect cross sections of this order of magnitude and perhaps smaller than this.

We note that the search for muonless ν_μ interactions may also have significance for the search for $\Delta S = 0$ weak neutral currents. The present limits on the existence of such currents is very poor, especially for any appreciable momentum transfer.

(b) Experimental Detection

The search for muonless ν_μ interactions is well suited to a Ne filled bubble chamber of the size being built at NAL. The primary advantage of the heavy liquid chamber is the separation of the ν_μ induced muonless process and the hadronic interactions in the bubble chamber such as high energy neutrons interactions. The ν_μ induced processes should be uniform over the chamber volume whereas hadron induced processes will show a characteristic fall off in the downstream part of the bubble chamber.

The unique identification of the absence of a muon in the final state will probably require some help from an absorber placed outside the bubble chamber. With the directions and momentum of the charged particles that do not interact in the bubble chamber known, it will then be possible to predict whether a given charged particle should penetrate the absorber or not. Events for which any charged particle, if it were a muon, does not penetrate the absorber will, therefore, be candidates for muonless interactions.

Thus this phase of the experiment may require a plate in the bubble chamber or the EMI. We would, therefore, consider that the experiment proposed here will be primarily useful for understanding the backgrounds for the eventual detection of muonless neutrino interactions.

5. Diffraction Dissociation of ν_μ's on Neon

The process

$$\nu_\mu + Z \to \mu^+\mu^-\nu_\mu + Z$$

can be considered as a dissociation process of the form $\nu_\mu \to \mu^+\mu^-\nu_\mu$ in the Coulomb field of the nucleus. By analogy there should be other dissociation processes of the ν_μ with hadrons in the final state. These processes were discussed in the 1968 summer study by Cline.[7] Examples of these processes are:

$$\begin{aligned} \nu_\mu &\to \mu^- + \pi^+ && (\pi \text{ Beta decay}) \\ &\to \mu^- + \rho^+ \to \mu^- + \pi^+ + \pi^\circ && (\rho \text{ Beta decay}) \\ &\to \mu^- + A_1^+ \to \mu^- + \pi^+ + \pi^+ + \pi && (A_1 \text{ Beta decay}) \\ &\to \mu^- + K^* \to \mu^- + K^\circ + \pi^+ && (K^* \text{ Beta decay}) \\ &\to \mu^- + Q^+ \to \mu^- + K + \pi + \pi && (Q \text{ Beta decay}) \end{aligned}$$

with the dissociation occuring in the field of the nucleus. We know the coupling for process 1 through π decay but all other couplings are presently unknown, and indeed this is the purpose of the experiment.

These processes will occur with very small momentum transfer to the μ^- and to the hadrons. The advantage of the Ne bubble chamber here is one primarily one of rate and the possibility of $E\nu$ energy measurements using the converted photons. We expect to be able to reconstruct the $\pi^+\pi^\circ$ mass and obtain the momentum transfer to the recoiling nucleus, and thus to pick out the diffraction events from the deep inelastic background.

We have crudely estimated the cross section for these processes to be $\gtrsim 10^{-38} cm^2$/Ne nucleus for $E\nu > 5$ GeV. This estimate agrees with the calculation of B. Roe (P. R. L. 21, 1666 (1968)) who obtains $\sim 4 \times 10^{-38}$. On the basis of this cross section we have estimated the number of events obtained in certain momentum bands. For example, for $E\nu = 15$-25 GeV the exposure would yield $\sim$ 100 events and for 75-115 GeV approximately 250 events. Thus we expect in the complete exposure $\sim$ 1000's of events. For example, it should be possible to measure the ρ and K^* decay density matrix elements.

6. Study of Deep Inelastic ν_μ Scattering on Neon

The theoretical interest in studying deep inelastic scattering with neutrinos is now well known and has been reviewed extensively, and we will not repeat the arguments here.[9] We present here, the rate and experimental detection method.

For the deep inelastic scattering, we will use a very restricted fiducial volume in the upstream end of the bubble chamber of 3 x 3 x 1 m in volume. In a 250,000 picture run, assuming that the total cross section continues to rise linearily, we expect the event rates tabulated in table 1.

The event rates tabulated in table 1 indicate that, if adequate $E\nu$ energy measurements can be obtained, the total ν cross section could be measured up to $\sim$ 150 GeV in the exposure proposed here. Of course, there may be problems with ν flux estimates and the energy measurements must be calibrated by putting high energy π mesons into the system.

The use of a highly restricted fiducial volume in the front of the chamber should allow good neutrino energy measurements (there will be $\sim$ 8 radiation lengths beyond the fiducial region) and adequate muon identification (there will be $\sim$ 4 collision lengths beyond the fiducial region).

Measurement of $E\nu$ and E_μ will allow ν and q^2 to be computed for each event. The event rate appears to be adequate to obtain considerable information about the behavior of the deep inelastic ν_μ scattering.

It will also be possible to obtain considerable information about the hadrons that accompany the deep inelastic collisions; such as the multiplicity and $P_\perp$ distribution and certainly will be possible to observe resonance production such as ρ, ω, etc. in the final state.

The μ^- will be separated from π^-'s on a statistical basis. Since there are 4 collision lengths beyond the fiducial volume we estimate that the separation will be good to $\sim$ 10%. Thus we do not need an EMI or the plate for the study of deep inelastic scattering. However, we feel strongly that the plate would be very useful and perhaps crucial for some experiments such as the detection of μ less neutrino interactions. We urge the laboratory to provide a plate for the bubble chamber as soon as possible.

Table 1

Number of Events in a 3 x 3 x 1 m

Fiducial Volume in the Neon Bubble Chamber (Horn Focus assumed)

(250 K pictures)

Energy Interval (GeV)	Number of Events	Energy Interval (GeV)	Number of Events
5 - 15	100,000	95 - 105	250
15 - 25	70,000	105 - 115	150
25 - 35	18,000	115 - 125	90
35 - 45	6,000	125 - 135	75
45 - 55	3,000	135 - 145	60
55 - 65	3,000	145 - 155	30
65 - 75	1,800		
75 - 85	1,000		
85 - 95	500		

7. Test of the $\Delta S = \Delta Q$ Rule with Inclusive Strange Particle Reactions

The $\Delta S = \Delta Q$ rule is now well tested to the level of $\sim$ (1-2)% in the amplitude using K and Σ decays. These tests are at predominately low momentum transfer. We wish to test this rule at high momentum transfer using high energy neutrino reactions. We propose, therefore, the following procedure:

Search for reactions of the type

$$\nu_\mu + N \to \Lambda + \mu^- + (\text{all})^{\pm +}, \tag{1}$$

where it can be shown experimentally that no other strange particles are included in the $(\text{all})^{\pm +}$. In this case reaction (1) would require a $\Delta S = -\Delta Q$ current. Since reaction (1) is an inclusive reaction (or a deep inelastic reaction) it is probable that high momentum transfers from the $\nu_\mu \to \mu^-$ can be obtained and thus this would provide a test of $\Delta S = \Delta Q$ at high Q^2.

The corresponding allowed reaction would be

$$\bar{\nu}_\mu + N \to \Lambda + \mu^+ + (\text{all})^{\circ} \tag{2}$$

which is again an inclusive reaction and perhaps exhibits a linear rise in the cross section with $E\nu$. The cross section of reaction (2) for a given Λ configuration, Q^2 and $E\nu$ as compared to the cross section for (1) then provides the ratio of $\Delta S = \Delta Q$ to $\Delta S = -\Delta Q$ amplitudes at this Q^2.

We propose to search for reaction (1) to investigate the feasibility of testing selection rules via such inclusive reactions. Experimentally, reaction (1) can only be detected using a detector with the analytical power of the Ne 15' bubble chamber. The possible final states that must be suppressed are

$$\nu_\mu + N \to \Lambda + \mu^- + K^+ + (\text{all}) \tag{3}$$

$$\nu_\mu + N \rightarrow \Lambda + \mu^- + K^\circ + (\text{all}) \tag{4}$$

$$\rightarrow \Lambda + \mu^- + \bar{\Lambda}(\bar{\Sigma}) + (\text{all}) \tag{5}$$

Because of the large number of collision lengths in the Ne bubble chamber, if events of signature for type 1 are taken in an appropriate fiducial volume in the middle of the bubble chamber, we suspect that it will be possible to uniquely identify the majority of events of reactions (3), (4) and (5) through $(K,\bar{K})$ or $\bar{B}$ interactions or decays. Knowing the characteristics of $(K,\bar{K})$ interactions in Ne would allow us to correct for the events where the $(K,\bar{K})$ escaped before interacting.

We feel that the search for reaction (1) (and subsequent study of reaction 2) may provide an important experimental technique for testing weak interaction selection rules. The present experiment can be used to initially test this idea.

8. Energy Estimates Inside Versus Outside the Bubble Chamber

We have considered various techniques for estimating the incident neutrino energy including the use of a calorimeter outside the bubble chamber as suggested for counter experiments in NAL proposal number 1.[8]

We feel that there are severe difficulties in the use of such calorimeter devices in bubble chambers because of the possibility of over counting the energy. For example high energy ν interactions will undoubtedly produce large numbers of mesons. The π meson interactions in the walls or coils of the bubble chamber will produce photons which are then counted again in the calorimeter. Thus this technique has inherent disadvantages, when used with a visual device, compared to the direct measurement of the energy in the bubble chamber. It is not clear that the $E\nu$ measurement is superior in the former case. (See Appendix 1 for a discussion of the energy measurement question.)

Pure neon has a radiation length of $\sim$ 24 cm, thus, the bubble chamber is $\sim$ 12 radiation lengths across. By taking a restricted fiducial volume, it will be possible to obtain rates that are several times as large as that obtained using the entire bubble chamber for H_2, and at the same time adequate energy measurements of the photons that accompany the hadronic shower. There is no reason why the measurement of the energy dependence of the $(\nu_\mu + n)$ and $(\nu_\mu + p)$ cross section can't be carried out as well in Neon as in hydrogen. Likewise, the study of scale invariance using the deep inelastic ν_μ scattering is not compromised using neon. However, the detailed study of the multipion final states will be somewhat more difficult, because of interactions in the nucleus. Past experience, as well as the CERN ν experiments lead us to believe that useful final state studies can be done in the Ne bubble chamber.

It should be noted that a heavy liquid chamber is also useful in identifying K^- mesons by observing secondary interactions in which a Λ or Σ is produced.

We expect that the Neon bubble chamber will allow $E\nu$ measurements that are appreciably better than that obtained in the CERN experiments.

9. Conclusions and Detailed Proposal

We have proposed an experiment designed specifically to search for the existence of new heavy leptons or other new penetrating radiation. Order of magnitude calculations of the rate for the production of 3 GeV heavy lepton pairs are encouraging and suggest that there is a good probability of detection. We emphasize that the production rates could be large and the detection easier. The use of a heavy liquid bubble chamber has many advantages in the search for heavy leptons and other new phenomena, and, of course, provides much greater event production rates than hydrogen. The large information gathering power of a heavy liquid chamber coupled with the large mass provides an advantage when searching for totally new phenomena produced when 400 GeV protons interact in the shield. We, therefore, request that the experiment proposed here be considered for an early running time after machine operation.

In conclusion, we request 2.5×10^5 pictures of the Ne bubble chamber with protons incident on the shield and 2.5×10^5 with the ordinary horn focused (or unfocused) ν_μ beam. (If horn focusing is not available at the earliest time, the heavy lepton search will not be affected and there will still be adequate event rates to study the deep inelastic scattering). We would be willing to run with almost any Ne - H_2 mixture also that is Ne rich.

References

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9. See, for example, J. D. Bjorken and E. A. Paschos, Report No. SLAC-PUB-678, 1969 or A. Pais, 'Weak Interactions at High Energies', presented at the Wisconsin Conference on 'Expectations for Particle Reactions at the New Accelerators'.

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Appendix I

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NEUTRINO-ENERGY ESTIMATES IN A Ne BUBBLE CHAMBER

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ABSTRACT

Using the NAL bubble chamber filled with Ne on restricting events to a small fiducial volume upstream in the bubble chamber, it should be possible to measure the average energy of the incident neutrino to ~ 6% and to identify muons in the final state on a statistical basis. Because of the large mass available and the possibility of making E_ν estimates entirely within the bubble chamber, the Ne bubble chamber should provide a powerful tool in the early exploration of ν_μ interactions at NAL.

A possible configuration for doing neutrino experiments in the NAL large bubble chamber is to fill the chamber with pure neon and to use a small fiducial volume region in the upstream end of the bubble chamber as the target. This possibility is discussed in Proposal 28. Since the bubble chamber contains ~ 30 tons of Ne, it is easy to choose an ~5-ton fiducial volume. The remainder of the bubble chamber is used to measure the charged-particle energies by curvature, the π^0 energy by converting the photons, measuring directly by curvature the e^+e^- energy and for μ identification. A fiducial volume of 1m × 2m × 2m can be used which contains 4.8-metric tons of Ne or approximately 1/6 of the entire Ne in the bubble chamber. This is about 5 times more material than for the entire hydrogen chamber. The remainder of the chamber then provides ≥ 8 radiation lengths in the forward direction (X_0 = 24 cm for Ne) and out to 30° and ~3 collision lengths (l_c ~ 60 cm for Ne). The 3 collision lengths provide ~95% probability that a hadron will scatter (including diffraction scattering which should be detectable). Thus, a reasonably good statistical separation of fast π's and fast μ's should be possible.

Since most of the photon energy should be converted within 4 radiation lengths after the target, it should be possible to accept more than one event per picture and perhaps as many as three. In the latter case the experiment would then yield an event in the target fiducial volume every other bubble-chamber picture. Since the rates in the Ne bubble chamber are ~ 30 times greater than hydrogen with the configuration discussed here, a neutrino-beam intensity of ~ 15 times less than that required for the bubble chamber would be adequate. Thus these experiments are almost parasitic at NAL.

To estimate the incident-neutrino energy, the energy of the charged hadrons and π^0's must be obtained. We assume that the dominant uncertainty for the charged particle tracks comes from multiple-coulomb scattering. We also assume that 50 cm will be available for this measurement since the collision length is ~ 60 cm. The $\Delta p/p$ for each track will be, assuming a 30-kG field,

$$\frac{\Delta p}{p} \sim \frac{57}{\beta H} \frac{1}{\sqrt{l X_0}} \sim 5.2\%, \; (l = 50 \text{ cm}, \; X_0 = 24 \text{ cm})$$

for the high-energy mesons coming from the collision. If l = 150 cm is used, $\Delta p/p$ ~ 3%. The nuclear evaporation energy should be small and can be estimated by measuring the range of the proton recoils in the bubble chamber.

The estimate of π^0 energies is somewhat more speculative, but based on previous measurements in heavy-liquid chambers it appears that ~ 15% energy resolution is quite reasonable, and ~ 10% may be possible by measuring all the shower products. Note that a negligible fraction of the π^0 energy escapes the bubble chamber in the forward direction since there are 8 radiation lengths.

If we assume that on average there is 70% of the energy in charged particles and 30% in neutrals, then the average energy resolution would be

$$\frac{\Delta E}{E} \sim \sqrt{[0.7(0.05)]^2 + [0.3(0.15)]^2} \sim 6\%.$$

Thus, the worst energy measurement would be ~ 15% if all the hadrons were neutral and the best ~ 5.0%. It is unlikely that the average energy measurement would be worse than ~ 10% and better than 5%.

It appears that the Ne bubble chamber with a small fiducial-volume target of pure Ne can run on an almost-parasitic neutrino beam (or an unfocused ν beam) and that the incident ν energy can be estimated to (5-10)%.

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NAL PROPOSAL No. 28

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Search for Heavy Leptons; Study of Coulomb - Diffraction Dissociation of Neutrinos; Measurement of the Charge Radius of the ν_μ and the Study of Deep Inelastic ν_μ Scattering in a Ne Bubble Chamber at NAL

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Proposal

ABSTRACT

We propose here an experiment designed to search for the existence of heavy leptons ($\lambda^{\pm}$) produced in the collisions of 200 GeV/c protons with matter. These charged leptons, which are assumed to decay by weak interaction will be detected by the interactions of their neutrinos ($\nu_\lambda, \bar{\nu}_\lambda$) in a Ne bubble chamber. For leptons with masses of greater than 1 GeV, the λ life time is expected to be too short for the lepton to be observed visually, therefore, the lepton must be identified by a detailed comparison with ordinary ν_μ interactions. We request 500,000 pictures with the beam protons hitting the shield directly and 500,000 pictures with the normal horn focused high energy ν_μ beam. In the latter pictures we will study deep inelastic ν_μ scattering, search for muonless ν_μ interactions and search for ν_μ diffractive processes.

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1. Introduction

The existence of still heavier charged leptons than the muon is clearly of great interest. The discovery of these leptons would perhaps shed some light on the existence of the muon and the nature of the interaction responsible for the (μ-e) mass difference. We can anticipate two interesting aspects of such heavy leptons:

1. They will carry their own lepton number, therefore, suggesting the existence of a new neutrino.
2. It is likely that their lifetime will be sufficiently short so that direct discovery, say by a mass search, will be impossible even at NAL.

Therefore, in all probability, these heavy leptons will not easily reveal theirselves to us. In this proposal we suggest a technique of searching for heavy leptons ($\lambda\bar{\lambda}$) that are produced in the shield by either the incident protons or the large flux of electrons or photons obtained through π^0 production. This idea follows the experiment to be run at SLAC by Mann and Schwartz.[1] However, we believe that our sensitivity will be much greater. It is pointed out that the identification of ν_λ interactions and separation from the more copious ν_μ interactions is made possible through the combination of a visual technique and the unique features of a heavy liquid detector. The details of the proposed technique for a heavy lepton search at NAL will be discussed in sections 2 and 3.

There will be many fallout experiments from the Ne bubble chamber exposure proposed here. These experiments, which are of considerable interest in their own right and are unique to the Ne chamber, fall into several distinct categories which are discussed in sections 4, 5 and 6. In section 8 we discuss in detail the time scale and the magnitude of the exposure requested.

2. Production of Heavy Lepton Pairs by Protons and Sensitivity of the Heavy Lepton Search

(a) Heavy lepton pair production rates

1. Hadroproduction of $\lambda\bar{\lambda}$ pairs. We assume a $\lambda\bar{\lambda}$ production cross section of $\sim 10^{-33}$ cm^2/nucleon (this is the order of magnitude of the cross section observed by Christenson and Lederman in their AGS experiment). The number of $\lambda\bar{\lambda}$ pairs produced per pulse would be $\sim 2 \times 10^6$. The leptons should be strongly collimated forward.

2. Photoproduction of $\lambda\bar{\lambda}$ pairs. We expect that $\sim 10^{14}$ photons will be produced each pulse coming from π° decays. The rate of photoproduction of $\lambda\bar{\lambda}$ pairs goes like the inverse of the mass squared. The relative rate for $\lambda\bar{\lambda}$ production to e^+e^- production is given as

$$\left(\frac{m_e}{m_\lambda}\right)^2 \sim 10^7$$

for $m_\lambda = 3$ GeV. Using the fact that almost all the photons make e^+e^- pairs we find a $\lambda\bar{\lambda}$ production rate of

$$\sim 10^{14}/10^7 = 10^7 \lambda\text{'s/pulse}.$$

Electroproduction (from the electrons produced by pair production) and the decay of high mass vector mesons might also contribute a comparable rate.

Thus, it is not unreasonable to expect that the order of $\sim 10^6 - 10^7$ $\lambda\bar{\lambda}$ pairs will be produced each machine pulse. We assume that because of the strong collimation of the $\lambda\bar{\lambda}$, 10% of the $(\nu_\lambda,\bar{\nu}_\lambda)$'s from the λ decays will pass through the bubble chamber.

(b) Rate of Production of $(\lambda,\bar{\lambda})$'s in the Ne Bubble Chamber

Assuming a 15 ton fiducial volume of Ne we find that 5×10^5 pictures would give 10 events if there were 2.5×10^6 ν_λ's incident on the chamber per pulse. This assumes that the ν_λ interaction cross section is the same as that of ν_μ's of 10 GeV. This is the same order of magnitude of ν_λ flux that might be crudely guessed to come from interactions in the shield.

The order of magnitude guesses listed above for the $(\lambda,\bar{\lambda})$ production and for the ν_λ detections indicate that it is not unreasonable to expect that the production of heavy leptons in the shield could be detected in the bubble chamber.

3. Experimental Technique for the Detection of ν_λ

Heavy lepton production by $(\nu_\lambda, \bar{\nu}_\lambda)$ would occur through the processes

$$\nu_\lambda + n \to \lambda^- + \text{(anything)} \quad (1)$$

$$\bar{\nu}_\lambda + p \to \lambda^+ + \text{(anything)} \quad (2)$$

with the leptons decaying by

$$\lambda^\pm \to \pi^\pm \nu_\lambda \quad (3)$$

$$\lambda^\pm \to \mu^\pm \nu_\mu \nu_\lambda \quad (4)$$

It has been estimated that for $M_\lambda > 1$ GeV the decay processes (3) and (4) wi l be equally probably.[2] In addition it has been estimated that the lifetime of the $\lambda^\pm$ will be less than $\sim 10^{-11}$ seconds for $M_\lambda > 1$ GeV. Therefore, it would seem unlikely to directly observe the trajectory of the $\lambda^\pm$ even in a bubble chamber.

The most likely method of discovery for the $\lambda^\pm$ would be to infer the existence of these particles through the characteristics of the decay modes (3) and (4). In the case of decay modes (3) the event signature will be the observation of single or multiple $\pi^\pm$'s being produced with high transverse momentum relative to the neutrino beam direction. Provided such events can be separated from hadron interactions this will be a clean signature since ν_μ interactions will not usually produce a pion unaccompanied by a μ (see, however, section 4). Since ν_λ and $\bar{\nu}_\lambda$ are produced with equal rate in the shield equal numbers of fast π^+ and π^- events should be observed. Since the Ne bubble chamber is ≥ 6 collision lengths across, hadron produced events should be clustered near the entrance of the bubble chamber whereas ν_λ produced events will be uniformly spread out. For neutrons interactions that are in equilibrium with the ν_μ coming through the shield the interaction rate will scale with the ν_μ flux whereas the rate for λ production will be $\sim$ independent of the ν_μ flux.

The decay mode (4) may not provide a relatively unique signature in that these events would also look like ordinary ν_μ interactions with high transverse μ momentum. However, a detailed comparison of the μ transverse momentum distribution for a sample of events that were enriched with $\lambda^\pm$ production may yield evidence for λ production. The isolation of both decays (3) and (4) would provide very strong evidence for the existence of $\lambda^\pm$ leptons. Process (3) can perhaps be used to estimate the mass of the $\lambda^\pm$.

There will be two steps, therefore, in the experimental heavy lepton ($\lambda^\pm$) search, each requiring $\sim$ 500,000 pictures of the Ne bubble chamber;

A. The primary protons are transported all the way to the shield. Heavy leptons as well as the common strongly interacting particles will be produced. The heavy leptons as well as any other short lived particles all decay. However, the strongly interacting particles are absorbed within $\sim$ 1.5 collision length. The production of the new leptons is revealed through the ν_λ interaction in the Ne bubble chamber. The high energy ν_μ neutrinos coming from π and K decay are suppressed relative to those produced at the ν target by a factor of

$$\sim \frac{(1.5 \text{ collision length in Fe})}{600 \text{ M}} \simeq 1/3000$$

Thus, the background in the bubble chamber coming from ordinary ν_μ interactions is strongly suppressed. All events produced in the bubble chamber will be carefully studied for evidence of these anamolous neutrino interactions.

B. The primary proton beam is made to hit the ν target and ordinary ν_μ interactions in Ne are carefully studied. In particular the transverse momentum distribution of the select event configurations which are also signatures for heavy lepton production is studied as well as the production of events with single or multiple pion production.

The first test for anamolous events will be to check to see if the rate of these events scales like the neutrino flux. If the rate scales like the flux then the event is most likely due to ν_μ interactions or hadronic interactions coming from the hadrons produced in the back of the shield by ν_μ's.

Event configurations that do no scale as the flux and which appear anamolous compared to ordinary ν_μ interactions will be studied in detail.

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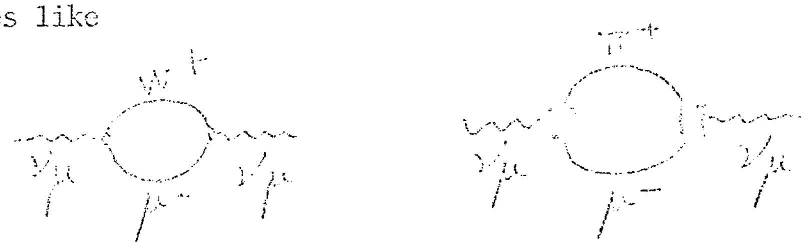
4. Attempt to Measure the Charge Radius of the Muon Neutrino - Detection of Muonless Neutrino Interactions

(a) Theory

The ν_μ is expected to have a charge radius due to virtual processes like



Diagrams of this type are expected to give a charge radius of the size $\langle r^2 \rangle_\omega \sim g^2\ (h/M_W c)^2 \sim Gm_n^2\ (h/M_n c)^2 \approx 10^{-32} (\text{cm.}^2)$[3,4,5,6] Protons can couple to the intermediate state charged particles subsequently resulting in electromagnetic scattering processes;

$$\nu_\mu + p \to \nu_\mu + p \tag{1}$$

$$\nu_\mu + p \to \nu_\mu + \text{(anything)} \tag{2}$$

Several estimates have been made for the rate of process (1) in terms of the W mass and of the cross section for

$$\nu_\mu + n \to \mu^- + p \tag{3}$$

Bernstein and Lee have estimated that process (1) will be down by $\sim 10^{-4}$ from process (3).[3] They find

$$d\sigma_{\nu\nu} = \left[\frac{1}{4}\ \frac{1}{137}\ \frac{(q^2 + M_W^2)}{M_W^2}\ f(q^2)\right]^2\ d\sigma_{\nu\mu} \tag{4}$$

where $f(q^2)$ is expected to be a slowly varying function of q^2. The term in brackets is proportional to the charge radius of the ν_μ neutrino. (For example single π production scattering can be written as

$$\frac{d\sigma(\nu p \to \nu p\pi)}{d\sigma(ep \to ep\pi)} = q^4/30\ \langle r^2 \rangle^2$$

where $\sqrt{<r^2>}$ is the ν_μ charge radius). For large W mass and large q^2 this gives $(f(q^2) \sim 4)$.[3]

$$d\sigma_{\nu\nu} \simeq 10^{-5}\ d\sigma_{\nu\mu}$$

Thus, for $\sim 10^5$ quasi elastic events there will be ~ 1 elastic ν_μ scatter. The collection of 10^5 quasi elastic events at high momentum transfer is a formidable task. However, present speculations lead to the expectation that the deep inelastic scattering cross section will be appreciable. Thus, if (4) continues to hold for these deep inelastic scatters (reaction 2) we expect

$$d\sigma_{\nu\mu \to \nu(\text{anything})} \simeq 10^{-5} \quad d\sigma_{\nu N \to \mu + \text{anything}}$$

or alternately in terms of the charge radius

$$d\sigma_{\nu N \to \nu(\text{anything})} = \frac{q4<r^2>^2}{32}\ d\sigma_{eN \to e + (\text{anything})},$$

for $q^2 = 10(\text{BeV}/c)^2$ and assuming $<r^2> \sim 10^{-32}\text{cm}^2$, this gives

$$d\sigma_{\nu N \to \nu + \text{anything}} \simeq 4 \times 10^{-39}\text{cm}.$$

Taking $e + N \to e + (\text{anything})$ cross sections as pessimistic a nanobarn (10^{-33} cm^2) we obtain

$$d\sigma_{\nu N \to \nu + (\text{anything})} \simeq 4 \times 10^{-39}\ \text{cm}.$$

With the apparatus described in this proposal we expect to be able to detect cross sections of this order of magnitude and perhaps smaller than this.

We note that the search for muonless ν_μ interactions may also have significance for the search for $\Delta S = 0$ weak neutral currents. The present limits on the existence of such currents is very poor, especially for any appreciable momentum transfer.

(b) Experimental Detection

The search for muonless ν_μ interactions is well suited to a Ne filled bubble chamber of the size being built at NAL. The primary advantage of the heavy liquid chamber is the separation of the ν_μ induced muonless process and the hadronic interactions in the bubble chamber such as high energy neutrons interactions. The ν_μ induced processes should be uniform over the chamber volume whereas hadron induced processes will show a characteristic fall off in the downstream part of the bubble chamber.

The unique identification of the absence of a muon in the final state will probably require some help from an absorber placed outside the bubble chamber. With the directions and momentum of the charged particles that do not interact in the bubble chamber known, it will then be possible to predict whether a given charged particle should penetrate the absorber or not. Events for which any charged particle, if it were a muon, does not penetrate the absorber will, therefore, be candidates for muonless interactions.

5. Diffraction Dissociation of ν_μ's on Neon

The process

$$\nu_\mu + Z \to \mu^+\mu^-\nu_\mu + Z$$

can be considered as a dissociation process of the form $\nu_\mu \to \mu^+\mu^-\nu_\mu$ in the Coulomb field of the nucleus. By analogy there should be other dissociation processes of the ν_μ with hadrons in the final state. These processes were discussed in the 1968 summer study by Cline[7]. Examples of these processes are:

$$\begin{aligned} \nu_\mu &\to \mu^- + \pi^+ \\ &\to \mu^- + \rho^+ \\ &\to \mu^- + A_1^+ \\ &\to \mu^- + K^{**} \\ &\to \mu^- + Q^+ \end{aligned}$$

with the disociation occuring either in the field of the nucleus or the Coulomb field.

These processes will occur with very small momentum transfer to the μ^- and to the hadrons. The advantage of the Ne bubble chamber here is one primarily one of rate and the possibility of $E\nu$ energy measurements using the converted photons.

6. Study of Deep Inelastic ν_μ Scattering on Neon

The theoretical interest in studying deep inelastic scattering with neutrinos is now well known and has been reviewed extensively, and we will not repeat the arguments here.[9] We present here, the rate and experimental detection method.

For the deep inelastic scattering, we will use a very restricted fiducial volume in the upstream end of the bubble chamber of 3 x 3 x 1 m in volume. In a 500,000 picture run, assuming that the total cross section continues to rise linearily, we expect the event rates tabulated in table 1.

We have used the latest flux calculates of Nezrich and Kang for this estimate. These event rates imply that there will be $\sim$ 3 events in the whole chamber every pulse. The beam intensity may have to be reduced somewhat to keep down the confusion for the neutrino energy measurement. We note that the event rate in the fiducial region is approximately 6 times larger than for a H_2 experiment.

The event rates tabulated in table 1 indicate that, if adequate E_ν energy measurements can be obtained, the total ν cross section could be measured up to $\sim$ 150 GeV in the exposure proposed here. Of course, there may be problems with ν flux estimates and the energy measurements must be calibrated by putting high energy π mesons into the system.

The use of a highly restricted fiducial volume in the front of the chamber should allow good neutrino energy measurements (there will be $\sim$ 8 radiation lengths beyond the fiducial region) and adequate muon identification (there will be $\sim$ 4 collision lengths beyond the fiducial region).

Measurement of E_ν and E_μ will allow ν and q^2 to be computed for each event. The event rate appears to be adequate to obtain considerable information about the behavior of the deep inelastic ν_μ scattering.

It will also be possible to obtain some information about the hadrons that accompany the deep inelastic collisions; such as the multiplicity and $P_\perp$ distribution.

Table 1

Number of Events in a 3 x 3 x 1 m

Fiducial Volume in the Neon Bubble Chamber

(500 K pictures)

Energy Interval (GeV)	Number of Events	Energy Interval (GeV)	Number of Events
5 - 15	200,000	95 - 105	550
15 - 25	140,000	105 - 115	290
25 - 35	37,000	115 - 125	180
35 - 45	12,000	125 - 135	150
45 - 55	6,700	135 - 145	125
55 - 65	6,000	145 - 155	66
65 - 75	3,700		
75 - 85	2,000		
85 - 95	1,100		

7. Energy Estimates Inside Versus Outside the Bubble Chamber

We have considered various techniques for estimating the incident neutrino energy including the use of a calorimeter outside the bubble chamber as suggested for counter experiments in NAL proposal number 1.[8]

There are severe difficulties in the use of such calorimeter devices in bubble chambers because of the possibility of over counting the energy. For example high energy ν interactions will undoubtly produce large numbers of mesons. The π meson interactions in the walls or coils of the bubble chamber will produce photons which are then counted again in the calorimeter. Thus this technique has inherent disadvantages, when used with a visual device, compared to the direct measurement of the energy in the bubble chamber. It is not clear that the E_ν measurement is superior in the former case.

Pure neon has a radiation length of $\sim$ 24 cm, thus, the bubble chamber is $\sim$ 12 radiation lengths across. By taking a restricted fiducial volume, it will be possible to obtain rates that are several times as large as that obtained using the entire bubble chamber for H_2, and at the same time adequate energy measurements of the photons that accompany the hadronic shower. There is no reason why the measurement of the energy dependence of the $(\nu_\mu + n)$ and $(\nu_\mu + p)$ cross section can't be carried out as well in Neon as in hydrogen. Likewise, the study of scale invariance using the deep inelastic ν_μ scattering is not compromised using neon. However, the detailed study of the multipion final states will be somewhat more difficult, because of interactions in the nucleus.

It should be noted that a heavy liquid chamber is also useful in identifying K^- mesons by observing secondary interactions in which a Λ or Σ is produced.

We expect that the Neon bubble chamber will allow E_ν measurements that are appreciably better than that obtained in the CERN experiments.

8. Conclusions and Detailed Proposal

We have proposed an experiment designed specifically to search for the existance of new heavy leptons. Order of magnitude calculations of the rate for the production of 3 GeV heavy lepton pairs are encouraging and suggest that there is a good probability of detection. We emphasize that the production rates could be larger and the detection easier. The use of a heavy liquid bubble chamber has many advantages in the search for heavy leptons and, of course, provides much greater event production rates than hydrogen. The large information gathering power of a heavy liquid chamber coupled with the large mass provides an advantage when searching for totally new phenomena produced when 200 GeV protons interact in the shield. We, therefore, request that the experiment proposed here be considered for an early running time after machine operation.

In conclusion, we request 5×10^5 pictures of the Ne bubble chamber with protons incident on the shield and 5×10^5 with the ordinary horn focused ν_μ beam. (If horn focusing is not available at the earliest time, the heavy lepton search will not be affected and there will still be adequate event rates to study the deep inelastic scattering). We would be willing to run with almost any Ne - H_2 mixture also that is Ne rich.

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